Intergalactic Matter And Cocoons of Radio Galaxies

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Abstract

The cocoons surrounding powerful radio sources can be extensive if the jet that feeds the cocoon is light and supersonic. They have been shown to remain overpressured with respect to the ambient medium for most of the life time of the sources. The observed lobes of the radio sources form parts of these extensive cocoons. We show that observations of the lobes of giant radio sources allow one to estimate the *density* of the intergalactic medium (IGM) in which the lobes are embedded. We estimate the IGM density to be of the order of a few percent of the closure density of the universe. We further calculate the radio power of the overpressured cocoon as a function of time and the ambient density.

Subject headings: galaxies: intergalactic medium, jets; cosmology: miscellaneous.

1 Introduction

The standard scenario for strong double radio sources involves a 'cocoon' surrounding the core and the jet, and consisting of shocked ambient medium and shocked jet material (Scheuer 1974; Blandford and Rees 1974). It has long been evident that supersonic, low-density jets deposit most of their energy in the cocoon, which acts as a "wastebasket" (Scheuer 1974). Later studies and numerical simulations concentrated on the properties of the jet and the jet/cocoon interface but not much on the evolution of the extensive cocoon. It was also the general belief that the cocoons would expand quickly to reach an equilibrium with the ambient medium.

Recently, however, Begelman and Cioffi (1989; hereafter BC) argued that the cocoons remain overpressured with respect to the ambient medium for a long time, and that for

many sources, they have not yet reached a state of equilibrium. They then used this fact to address the problem of jet confinement by the ram pressure of the cocoon. Their simple model has been numerically verified (Loken *et al.*1992; Cioffi and Blondin 1992). The picture that emerges from these studies is that of a overpressured, jet-nourished cocoon, whose length and width depend on the balance of the ram pressure of the ambient medium with, respectively, the jet's momentum flux and the cocoon pressure.

We will not be concerned with the problem of confining the jet in the present work, but rather the physical conditions in the cocoon and in the ambient medium. Before BC pointed out the tendency of the cocoons to remain overpressured, it was generally assumed that the pressure in the lobes of giant galaxies (whose lobes lie in the IGM, much beyond the hot corona of the host galaxy) also estimated the pressure of the IGM, as the time for the cocoons to reach pressure equilibrium with the IGM was thought to be short. That, however, does not seem to be the case (see also Subramanyan and Saripalli 1993). Here we ask the question whether observations of the lobes can say anything about the physical conditions of the IGM.

We find that following the simple model of BC, one can estimate the *density* of the ambient medium and one can therefore estimate the baryon density of the IGM from the observations of the giant radio sources. We also calculate the radio power of the cocoon and its dependences on the density of the ambient medium and time.

We discuss the density of the ambient medium in §3 and the radio power in §4. Throughout the paper, we use a Hubble constant of $H = h_{50}50$ km s^{-1} Mpc $^{-1}$. We also express the relevant densities in terms of the closure density of the universe (i.e., $\Omega = 1$ means a density of $\rho = (3H^2/8\pi G)$. We begin with a brief recapitulation of the important aspects of the BC model in the next section.

2 Overpressured Cocoons

Consider the extensive cocoons produced by light and hypersonic jets. The lightness of the jet means that the density of the fluid material in the jet ρ_j is smaller than that of the ambient medium ρ_a; i.e. $\eta = \rho_j/\rho_a < 1$ (hereafter, the subscripts j, a, c will refer to the jet, the ambient medium and the cocoon, respectively). We will not consider heavy or subsonic jets. Heavy jets behave like 'bullets' and do not form cocoons. And since the jet luminosity is proportional to M_h^3 (M is the Mach number of the head of the jet with respect to the sound velocity of the ambient medium), high luminosity of the classical double jet implies hypersonic, if not supersonic, jets.

The jet power L_j is assumed to be constant in time, for simplicity. The velocity of the head of the jet v_h is determined by the balance of the thrust of the jet ($\sim L_j/v_j$; we assume $\beta_j = v_j/c \sim 1$, as in BC) spread over the cross sectional area A_h of the bow shock at the end of the jet, and the ram pressure of the ambient medium. This yields (eqn. 1 of BC)

$$v_h \sim \Big(\frac{Lj}{\rho_a v_j^3 A_h}\Big)^{1/2} v_j \ . \qquad (1)$$

Notice that A_h can be much larger than the cross-section of the jet itself (as in the 'dentist drill' scenario (Scheuer 1982)). BC inferred a value of $A_h \sim 30$ kpc ^{2} for Cygnus A from observations. In their numerical simulation, Cioffi and Blondin (92) found that A_h increases with time (roughly, $A_h \propto t^{0.4\pm0.1}$ depending on the value of η), and therefore, v_h decreases with time, albeit slowly. In the light of its slow variation in time, and the uncertainties in other variables involved in the problem, we will use a constant A_h below.

The cocoon pressure p_c is obtained simply from the total energy deposited by the jet inside the volume of the cocoon $V_c = \epsilon_V (2\pi r_c^2) l_h$, where r_c is the half-width of the cocoon at the center, $l_h = \int v_h dt$ is the length of the jet head and ϵ_V is a volume factor depending on the shape of the cocoon (see Fig. 1). For a cylindrical cocoon, $\epsilon_V = 1$ and for a biconical shape, it is $\sim 1/3$ (Loken *et al.*1992). One thus obtains

$$p_c \approx \frac{(\gamma-1)L_j t}{V_c} \approx \rho_a \Big(\frac{dr_c}{dt}\Big)^2 \,, \tag{2}$$

where the second equality comes from balancing the cocoon pressure with the ram pressure of the ambient medium. γ is the adiabatic index of the material in the cocoon. This readily yields upon integration an expression for the size of the cocoon, as

$$r_c^2 \approx \Big(\frac{6(\gamma-1)}{\pi}\Big)^{1/2} \Big(\frac{L_j v_j A_h}{\rho_a}\Big)^{1/4} \Big(\frac{\epsilon_V}{1/3}\Big)^{-1/2} t \,. \tag{3}$$

Eqn (1) and (2) can then be combined to give the cocoon pressure, as

$$p_c \approx \Big(\frac{9(\gamma-1)}{24\pi}\Big)^{1/2} \Big(\frac{L_j \rho_a}{v_h}\Big)^{1/2} \Big(\frac{\epsilon_V}{1/3}\Big)^{-1/2} t^{-1} \,. \tag{4}$$

Cioffi and Blondin (1992) argued on the basis of their simulation that initially the cocoon energy is not totally thermalized and it is about equally divided between thermal and kinetic energy. However, at later times, the fraction of the thermalized energy approaches unity.

The last equation (eqn (4)) allows us to estimate the time t_{eq} for the cocoon to reach pressure equilibrium with the ambient medium, after which the cocoon boundary expands at the sound speed of the ambient medium. For powerful radio galaxies, with length-scales of the order of Mpc, the ambient medium is the IGM. We can write the equilibrium time scale as,

$$\begin{aligned} t_{eq} &\approx \frac{\mu m_p}{k T_a} \Big(\frac{L_j v_j A_h}{\rho_a}\Big)^{1/4} \Big(\frac{9(\gamma-1)}{24\pi}\Big)^{1/2} \Big(\frac{\epsilon_V}{1/3}\Big)^{-1/2} \\ &\sim 1.34 \times 10^{10} (T_{a,6})^{-1} \Omega_{IGM}^{-1/4}\, h_{50}^{1/2}\, L_{j,45}^{1/4}\, \beta_j^{1/4} A_{h,30}^{1/4} \Big(\frac{\epsilon_V}{1/3}\Big)^{-1/2} \text{ yr.} \end{aligned} \tag{5}$$

Here, $\mu \sim 0.6$ is the mean molecular weight, $T_a = 10^6 T_{a,6}$ K is the temperature of the IGM gas, and k is the Boltzmann's constant. We have expressed L_j and A_h in the units of 10^{45} erg s^{-1} and 30 kpc^2 respectively, in accordance with BC. Whereas the earlier studies (BC; Cioffi and Blondin 1992, and Loken *et al.*1992) used a value of $T_a \sim 10^8$ K, motivated

by hot IGM models for the X-ray background, thus obtaining $t_{eq} \sim 10^8$ yr, a much lower temperature of the IGM seems more reasonable. The constraint from the COBE limit on the Compton y parameter ($y < 2.5 \times 10^{-5}$, Mather *et al.*1993) and the anisotropy measurements of the microwave background radiation in arcminute scales ($\frac{dT}{T} < 10^{-5}$, Subrahmanyan *et al.*1993) pose severe problems with hot IGM models for the X-ray background (e.g., Loeb 1991). Moreover, success of the discrete source models in explaining the X-ray background (Zdziarski, Życki, Krolik 1993) has diminished the motivation for such a hot IGM. Instead, models of a photoionized IGM favour temperatures as low as $\sim$ few $\times\, 10^4$ K (e.g., Miralda-Escudè and Ostriker 1990). Therefore, eqn (5) suggests a equilibrium time scale that can be even larger than the Hubble time ($\sim 1.3 \times 10^{10} h_{50}^{-1}$ yr, for a $\Omega = 1$ universe). The cocoons then stay overpressured with respect to the IGM for all relevant times in the evolution of the giant radio sources, unless L_j, A_h have values much different than those used above.

We now turn our attention to the determination of the ambient density of radio sources, in particular, the IGM density from the observations of giant radio sources.

3 Intergalactic Matter

The pressure jump across the cocoon boundary can be calculated if the bow shock surrounding the supersonic jet is approximated as a steady, oblique shock (Loken *et al.*1992). The gas in the cocoon is separated from the shocked ambient gas with pressure $p_{sh,a}$ just inside the bow shock (i.e., downstream) by a contact discontinuity (i.e., $p_c \sim p_{sh,a}$). The pressure of the ambient medium p_a and the cocoon pressure $p_c (= p_{sh,a})$ are then related as (e.g., Landau and Lifshitz 1959),

$$\frac{p_c}{p_a} = \frac{5M_h^2 \sin^2\phi - 1}{4} \,, \tag{6}$$

where M_h is the Mach number of the head of the jet with respect to the sound speed of the ambient medium (c_{sa}). In other words, $M_h = v_h/c_{sa}$. ϕ is the angle that the bow shock makes with respect to the jet axis and $\gamma = 5/3$ is assumed for an ideal gas in the above equation.

For a large pressure jump ($p_c/p_a \gg 1$), eqn (6) can be rewritten in terms of the ambient density ρ_a,

$$\rho_a = \frac{4p_a}{3v_h^2 \sin^2\phi} \,. \tag{7}$$

Furthermore, since $v_h = l_h/t$ (for a constant v_h), this can also be written in terms of the age of the system t and the length of the jet l_h. Note that, eqn (7) is essentially eqn (2) in disguise: the transverse growth rate of the cocoon ($\frac{dr_c}{dt}$) is replaced by a term proportional to ($v_h \sin\phi$), since the former is hard to estimate.

(i) Radio galaxies inside clusters:

Before going over to the case of giant radio galaxies embedded in the IGM, let us use eqn (7) to estimate the ambient density for Cygnus A, which is inside a cluster, and whose

ambient density has been measured by X-ray observations. This will be a consistency check for our method. For Cygnus A, eqn (7) gives the ambient particle density $n_a (= \frac{\rho_a}{\mu m_p})$ as,

$$n_a \approx 2 \times 10^{-3} \Big(\frac{p_c}{8 \times 10^{-11}}\Big) \Big(\frac{t}{3 \times 10^7 yr}\Big)^2 \Big(\frac{l_h}{60\, kpc}\Big)^{-2} \Big(\frac{\sin(20^\circ)}{\sin\phi}\Big)^2 . \qquad (8)$$

From X-ray observations, one estimates the ambient pressure $p_a \sim 8 \times 10^{-11}$ dyne cm^{-2} and an ambient electron density of $\sim 6 \times 10^{-3}$ cm^{-3} (Arnaud *et al.*1987). A minimum age of $\sim 3 \times 10^7 L_{j,45}^{-1}$ yr is estimated from the minimum total energy ($\sim 10^{60}$ ergs) in the radio lobes (BC). The pressure jump is, therefore, of the order of ~ 3 if the angle of the bowshock is $\sim 20^\circ$, for which the aspect ratio of the cocoon, i.e. the ratio of the width to the length, is ~ 0.4.

(ii) Giant radio galaxies in the IGM:

Clearly, the angle ϕ is a difficult parameter to measure from the radio observations of the lobes. However, for $\phi \lesssim 30^\circ$ $\sin\phi \sim \tan\phi = r_c/l_h$, the difference being of the order of unity. We can then use eqn (3) to eliminate ϕ and rewrite the expression for the ambient density. For giant radio galaxies, the ambient density correspond to that of the IGM. We can express the IGM density as,

$$\Omega_{IGM} \approx 0.01 h_{50}^{-2} (1+z)^{-3}\, l_{h,Mpc}^{4/3} \Big(\frac{p_c}{10^{-14}\,\mathrm{d\ cm^{-2}}}\Big)^{4/3} \Big(\frac{v_h}{0.05c}\Big)^{-4/3} L_{j,45}^{-1/3} \beta_j^{-1/3} A_{h,30}^{-1/3} \epsilon_{V,1/3}^{2/3} . \qquad (9)$$

We have written the length of the jet l_h in the units of 1 Mpc, v_h in the units of $0.05c$ where c is the velocity of light, and the pressure p_c in cgs units. From the statistics of radio sources, Blandford and Rees (1984) estimated the limits of v_h as being $0.03c < v_h < 0.1c$. Therefore, an average value of $0.05c$ is reasonable. (Note that v_h is not a constant for all galaxies, as evident from eqn (1), and it increases with L_j. We have used an average value in eqn (9) only to give a feeling for the numbers. Also, note that there is no real evidence that such a value of v_h is also reasonable for giant sources; but here we assume that it is.) The pressure in the radio lobes of giant, with Mpc length scales, radio sources at low redshifts ($z \lesssim 0.1$) has been estimated from minimum energy arguments, as being of the order of 10^{-14} dyne cm^{-2} (Wagget, Warner and Baldwin 1977 obtained pressures $\sim 5 \times 10^{-14}$ dyne cm^{-2}; but see Subrahmanyan and Saripalli 1993). Recently, a giant source 8C 0821+695 at $z = 0.538$ has been discovered with $l_h \sim 1.5 h_{50}^{-1}$ Mpc and $p_c \sim 8 \times 10^{-14}$ dyne cm^{-2} (Lacy *et al.*1993).

An estimate of the jet luminosity (L_j) can be obtained from the product of the pressure in the hotspot, its apparent area and $v_j/2$ (e.g., Begelman, Blandford and Rees 1974).

It is worth while to note here that the estimates of the lobe pressure p_c (from minimum energy argument) scale as $h_{50}^{4/7}$ and l_h scales as h_{50}^{-1}. The overall dependency of Ω_{IGM} estimated from eqn (9) on the Hubble constant is then given by $h_{50}^{-18/7}$.

Requiring a overpressured cocoon, i.e. demanding $p_c \gtrsim p_a$, the lobe pressure observations can give an upper limit to the IGM pressure. Using the above estimate of the IGM density, one can thus put an upper limit to the temperature of the IGM gas, T_{IGM}. For Mpc long

radio sources, with lobe pressures $\sim 10^{-14}$ dyne cm^{-2} at the present epoch, an upper limit of $T_{IGM} \lesssim 10^7$ K is then implied.

To summarise this section: we have essentially used the transverse growth rate of the cocoons of radio sources to estimate the ambient density (eqns $(2, 7, 9)$), since the expansion of the cocoon in that direction is determined by the balance between the cocoon pressure (p_c) and the ram pressure of the ambient medium. We have used the shock jump conditions to relate the jet head velocity (v_h) and the aspect ratio of the cocoon, to the transverse growth rate, leading to eqns (7) and (9). For giant radio sources, this gives an estimate of the IGM density as a few percent of the closure density of the universe.

We will postpone a discussion on the cosmological implications of this estimate of the IGM density till §5, and calculate the radio luminosity of the overpressured cocoons in the next section. We will also discuss in §5 the uncertainties in the estimates of the lobe pressure that we have used above.

4 Radio Luminosity

The radio power of lobes which are expanding with an equal pressure ($p_a \sim p_c$) or expanding freely, with a subsonic velocity, has been calculated by various previous authors (e.g., Eilek and Shore 1989). We will calculate the radio luminosity in the case of the overpressured cocoons discussed above, mainly the way it scales with various parameters. We will follow the method outlined in Daly (1994).

The radio luminosity L_r of the cocoon at frequency ν is approximately $L_r(\nu) \approx \nu P_r(\nu)$, where P_r is the radio power at ν. If the rate of synchrotron emission per relativistic electron is dE/dt at the frequency ν and the number of relativistic electrons with energy E is $N(E)$, then the radio luminosity at the frequency ν can be approximately written as $L_r(\nu) \approx N(E)dE/dt$. The energy $E = \gamma m_e c^2$, where γ is the Lorentz factor. For a spectral index α at the radio frequencies (i.e., the radio luminosity is proportional to $\nu^{-\alpha}$), $N(E) = N_{tot}(\gamma/\gamma_l)^{-2\alpha}$, where γ_l denotes the lower cutoff in energy. N_{tot} is the total number of relativistic electrons in the cocoon, and in the limiting case that the total cocoon energy is in these electrons, can be written as $N_{tot} \approx (L_j t/\gamma_l m_e c^2)$.

The synchrotron emission rate $dE/dt \approx 1.6 \times 10^{-15}\gamma^2 B^2$, where the relativistic electron spirals around a magnetic field with $B_\perp$ as the component perpendicular to its velocity. Assuming equipartition between magnetic and gas energy, the magnetic field in the cocoon can be written (from eqn (3)) as $B \sim \left(\frac{16\pi\rho_a L_j}{v_h}\right)^{1/4} t^{-1/2}$. This readily leads to the radio power at the frequency ν, given by

$$P_r(\nu) \sim \frac{5 \times 10^{-8}}{(4 \times 10^6)^{(1-\alpha)}} (16\pi)^{\frac{1+\alpha}{4}} L_j^{\frac{5+\alpha}{4}} \rho_a^{\frac{1+\alpha}{4}} v_h^{-\frac{1+\alpha}{4}} \gamma_l^{(2\alpha-1)} \nu^{-\alpha} t^{\frac{1-\alpha}{2}} \,. \tag{10}$$

This predicts a small increase in the radio power with time for $\alpha \sim 1$ and with the ambient density ρ_a. Radio lobes in higher density environments would therefore have larger total luminosities. One should however remember that there is no direct evidence for the equipartition of energy that we have assumed (see below).

Note that P_r above is the total radio power of the cocoon. As emphasized by Loken *et al.*(1992), the radio luminosity will not be uniform throughout the cocoon. If the last reacceleration of the electrons happens at the Mach disk, the backflow velocity ($\sim$ sound speed in the cocoon, c_s) and the magnetic field B would limit the size of the lobe observed at a certain frequency ν. The size of the lobe will be $\sim c_s\tau_s$, where τ_s is the synchrotron life time of relativistic electrons with energies corresponding to the observed frequency, in the presence of magnetic field B.

However, it is possible that one will observe more extensive cocoons if reacceleration also happens elsewhere. It is also possible that if one uses beams that are sensitive enough to detect large structures, one could observe limb brightening at the cocoon boundary. This would provide support of the BC model for extensive cocoons.

It is interesting to note here that, at a given redshift, or in other words, at a constant ρ_a, $v_h \propto Lj^{1/2}$ (eqn (1)), which means that for a constant average v_h, the length of the radio source $l_h \propto v_h \propto L_j^{1/2} \propto P_r(\nu)^{\frac{2}{5+\alpha}}$. For $\alpha \sim 1$, this recovers the correlation $l_h \propto P_r^{0.3}$ that some observers claim to have found (e.g., Oort *et al.*1987). Other studies have also attempted to explain this correlation, although with specific models of structure of the ambient matter (Gopal-Krishna and Witta 1991).

5 Discussion

While using the lobe pressure p_c in determining Ω_{IGM} as in §3, the assumptions behind the estimates of p_c must be clearly borne in mind. Lobe pressure is usually calculated from the minimum energy arguments, which gives roughly the equipartition values. One of course does not have any direct evidence that equipartition holds in all cases, although sources embedded in clusters seem to yield pressure estimates that tally with X-ray observations. Also, the efficiency of energy conversion into relativistic electrons and magnetic field is not known. All these contribute to the uncertainty in the lobe pressure estimates.

It is also important to note that in reality most of the powerful radio galaxies are asymmetric and the diagram in Fig. 1 should be treated as being only schematic in nature. McCarthy, van Breugel and Kapahi (1991) have examined nonthermal radio emission from the plasma and line emissions from the thermal gas in a few of these asymmetric sources and suggested that the asymmetry is caused by density inhomogeneity.

Our estimate of the IGM density (§3) has important cosmological implications. First we note that a direct estimation of the density of IGM Ω_{IGM} has not been possible in the past and only indirect arguments has been put forward to place various limits (e.g., Barcons, Fabian and Rees (1991)). Primordial nucleosynthesis model limit the fraction of the baryonic density of the universe to $\Omega_b \sim (0.05 \pm 0.01)h_{50}^{-2}$ (Walker *et al.*1991). The luminous matter in galaxies at $z = 0$ contribute about $\Omega_{gal} \sim 0.007$, a similar amount in intracluster gas and some galactic or cluster baryonic dark matter may be present(Barcons, Fabian and Rees (1991)). They argued that a value of $\Omega_{IGM} \gtrsim 0.01$ is therefore reasonable. We note that our estimate of Ω_{IGM} from eqn (9) is consistent with these arguments.

Clearly, a homogeneous IGM is an ideal case and in reality the universe is probably clumpy. The size and magnitude of the clumpiness are still beyond our knowledge, though the clumping scale is limited by the upper limits of the anisotropy of the microwave background radiation, especially in the arcminute scale (Barcons, Fabian and Rees 1991). It is interesting to note that the estimates of lobe pressure in Mpc length radio sources do not vary much. Whether this indicates a selection effect or not, needs to be confirmed by looking for giant sources with low surface brightnesses (Lacy *et al.*1993). In any case, our estimates refer to the density in the vicinity of the radio source only and one ought to be cautious in drawing conclusions about the global homogeneity of the universe from a handful of giant radio sources.

If the IGM is rather uniform, then, one can constrain the temperature of the IGM gas from the limits on Compton y parameter from COBE along with the knowledge of Ω_{IGM} (as in Barcons, Fabian and Rees 1991, though the limit they used is now outdated by almost two orders of magnitude). However, this depends on the temperature and ionization history of the IGM, especially at high redshifts. Their argument against a hot IGM model for the production of the X-ray background radiation would however be strengthened by our estimate of Ω_{IGM} by narrowing the possible range of its value.

6 Conclusion

We have outlined a method to estimate the density of the intergalactic medium from observations of giant radio sources, in the framework of the model of overpressured cocoons surrounding these sources. We estimated an IGM density that is a few percent of the closure density of the universe. We also discussed the radio luminosity of the cocoons and found the model consistent with the observed correlation $l \propto P_r^{0.3}$.

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Figure Caption

Figure 1 – A schematic diagram of the cocoon surrounding a supersonic jet (see also the fig. 1 in BC and Loken *et al.*1993). The jet moves with velocity v_j and the head of the jet advances in the ambient medium (here the IGM) with velocity v_h and a with a cross sectional area A_h. The bow shock makes an angle ϕ with the jet axis and separates the ambient medium (with pressure P_a) from the shocked ambient medium (with pressure $P_{sh,a}$). There is a contact discontinuity between the shocked ambient medium and the cocoon gas (with pressure P_c). The width of the cocoon at the centre is r_c.

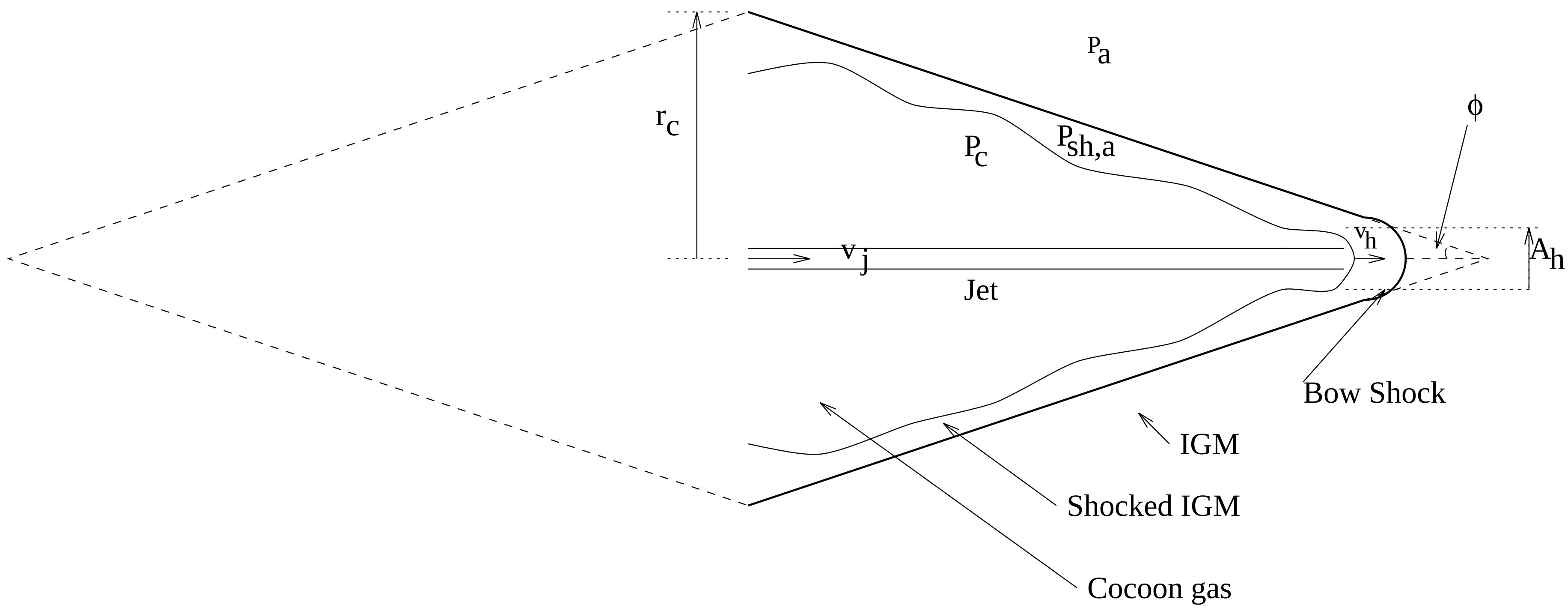
P_a
ϕ
r_c
P_c
$P_{sh,a}$
v_h
A_h
v_j
Jet
Bow Shock
IGM
Shocked IGM
Cocoon gas

Fig. 1